ON THE RADAR

JANUARY 19, 2019

Light Detection and Ranging (LIDAR)

A Technology Primer

BY JAKE HECLA

TYPE Sensors, Platform Control, and Information Support	**CHARACTERISTICS** Vantage, Range, Precision, Persistence	**RISK FACTORS** Vulnerable
DOMAIN Air, Sea	**COUNTRY** United States	

- Light detection and ranging (LIDAR) is an active-sensor technique that generates spatial data from the reflection of laser pulses from objects.
- The technique is useful for rapidly mapping terrain, chemical/biological weapons detection, demining, anti-submarine warfare, and scene-data-based navigation.
- LIDAR systems can be deployed on a diverse array of platforms, but they are most commonly used in commercial and military aviation systems.
- Underwater LIDAR systems are far more niche but are emerging onto the commercial market for marine mapping, law enforcement, and recovery operations.
- LIDAR technologies can augment strategic situational awareness (SA) through improvements in mapping, detection, and navigation.
- Applications for littoral anti-submarine warfare could have a major impact on the survivability of the submarine leg of the nuclear triad. Though the market for underwater LIDAR systems is small, advances in this field have the potential to have destabilizing consequences.

Introduction

Light detection and ranging (LIDAR) is an active-sensor technique that generates spatial data from the reflection of laser pulses from objects. Though the technique is best known for its use in rapidly mapping terrain, it has applications in chemical/biological weapons detection, demining, anti-submarine warfare, and scene-data-based navigation. Because of a robust private sector demand for unmanned aerial vehicle (UAV) and autonomous vehicle mapping and navigation capabilities based on LIDAR, the technology has advanced rapidly over the last decade. The strategic situational awareness (SA) improvements conferred by the addition of these technologies to existing platforms are wide-ranging. LIDAR based navigation presents significant improvements in persistence, whereas mapping and imaging applications offer improvements in precision, speed, and vantage. Because of the rapid commercialization of LIDAR devices, the availability, performance, and cost of these systems is rapidly improving. Therefore, these systems are likely to become increasingly relevant technologies for strategic SA.

Theory of Operation

LIDAR systems are based on time-of-flight optical range finding technology. Traditional LIDAR systems measure the timing of the reflection of microsecond-length laser pulses emitted from a rotating or scanning optical assembly (excepting phased-array LIDAR systems, which steer beams through purely optoelectronic methods). The time difference between the emission and the receipt of the reflected pulses then is used to determine the distance to the reflecting object. These systems typically use infrared (IR) emitters pulsed at tens to hundreds of kilohertz and have range capabilities of 100m to several km. Commercial systems range from narrow-beam speed detection systems to 360-degree mapping LIDAR devices for automated vehicle navigation. Specialized variants may use frequency ranges that are tailored for specific detector missions such as underwater sensing, through-cloud imaging, or aerosol detection.

For most commercial applications, the intent of the LIDAR data is to create human-viewable 3D maps of objects or terrain. In this case, the point-cloud data resulting from LIDAR scans can be filtered and colored using camera data, then further manipulated (typically converted to a mesh) to create a human-interpretable data product. This can be done in a highly automated fashion and can provide a highly detailed, human-readable 3D mapping capability in real time.

Simultaneous localization and mapping (SLAM) algorithms offer the ability to use LIDAR returns as a means of scene-aware navigation that does not require GPS or an accelerometer. SLAM algorithms use changes in the scene information (changes in the apparent location of features) to determine the rotation and translation of the detector system. By tracking the changes in orientation, the system can determine where it is in space, where it was in space, and how fast it is moving. This orientation information can be used to augment or replace accelerometer or gyroscope data, providing improved position estimation and redundancy. In some cases, this can be combined with previously-loaded map data to enable long-distance navigation without externally-dependent navigation systems (such as GPS, surface radio beacons, or GLONASS).

Specialized LIDAR systems can be used to detect aerosols, which can be used as means of mapping biological or chemical warfare agent releases. By using information on backscatter color, return ratio (fraction of reflected light), and changes in light polarization, the particulate size, composition, and density can be determined.[1] This capability was explored heavily by the U.S. military in the 1990s as a counter-WMD capability in the Long Range Biological Standoff Detection System (LR-BSDS). Likewise, these techniques can be used to pick up dust and smoke generated by vehicle movement or rocket launches, and potentially distinguish between them.

ViDAR (video detection and ranging), a technology closely related to LIDAR, offers a means of generating point-cloud data similar to LIDAR without the use of active sensing elements. This technique uses changes in image features extracted from video to reconstruct a 3D point cloud using a “structure from motion” (SfM) algorithm. Although this technique offers detailed colored reconstructions, it is extremely computationally intensive and therefore marginally viable as a real-time mapping or navigation aid.

---

[1] Aerosol detection methods in lidar-based atmospheric profiling. Mohamed I. Elbakary, Khan M. Iftekharuddin, Russell De Young, Kwasi Afrifa.

Operational Theater

LIDAR systems can be deployed on a diverse array of platforms but they are most commonly used in commercial and military aviation systems.

LIDAR systems can be deployed on a diverse array of platforms, but they are most commonly used in commercial and military aviation systems. The missions to which these systems are applied are widely varied. Mapping and navigation platforms based on LIDAR have been deployed on unmanned systems, including the AGM-129 cruise missile and the Airborne Laser Mine Detection System (ALMDS).[2] More recently, the DARPA HALOE (High Altitude LIDAR Operations Experiment) UAV provided high-rate 3D geospatial data to troops deployed in Afghanistan, allowing data collection rates over 1000km^2/hr (though the exact use of these data has not been stated). Nonmilitary aerial LIDAR survey systems have been used to gather data to reconstruct archaeological sites, monitor aircraft altitude (“laser altimetry”) and to map areas typically covered by fog or mist. Because of the ability of LIDAR to detect changes in landscape features, these systems also may be used to detect ground-level changes associated with mass graves or buried explosive devices.

Space-based LIDAR platforms exist, but little data from them is publicly available, and little is known regarding their exact capabilities. In theory, these systems allow a wide range of capabilities ranging from ground-mapping to aerosol characterization. Openly available information on ground-mapping systems indicate that they typically use wavelengths that allow through-cloud imaging, providing a means of data acquisition invulnerable to weather issues.

On the ground, land-based vehicles such as Lockheed Martin’s Squad Mission Support System (SMSS) have been equipped with LIDAR sensors for obstacle avoidance and mine detection. All autonomous ground vehicles use LIDAR systems as a means of obstacle avoidance because of the accuracy and high data rate they offer in comparison to ultrasound and radar. Further ground-based applications include scene-aware navigation, which does not require external signals (such as GPS), though no information has been made public indicating if any military systems use this technology.

At sea, LIDAR systems may augment anti-submarine warfare efforts (ASW) in littoral areas where sonar systems are limited by ship traffic noise and reflection.[3] Though limited by turbidity, existing bathymetric LIDAR systems offer a means of detecting underwater objects at depths of close to 100m.[4] Systems deployed on surface ships, aircraft or in fixed systems offer the ability to scan the water column in areas where traditional sonar signals would be lost in ambient noise or obfuscated by reflection. These systems may be deployed on aircraft, ships or on unmanned underwater vehicles (UUVs). Though a stand-alone LIDAR ASW capability has not been publicly demonstrated, it is likely that research and development efforts are underway to develop it.[5]

---

[2] Mark E. Kushina et al., "ALMDS laser system," In Solid State Lasers XII, 4968: 163–169. International Society for Optics and Photonics, 2003; National Research Council, *Laser Radar: Progress and Opportunities in Active Electro-Optical Sensing* (National Academies Press, 2014).

[3] John Olav Birkeland, “The potential of LIDAR as an antisubmarine warfare sensor,” PhD diss., University of Glasgow, 2009.

[4] Turbidity is a measure of the relative clarity of a liquid, determined by how much light is scattered by particles in the liquid when a beam is shone through it. See “Turbidity and Water,” U.S. Geological Survey, https://www.usgs.gov/special-topic/water-science-school/science/turbidity-and-water?qt-science_center_objects=0#qt-science_center_objects; Jennifer L. Irish, J.K. McClung, and W. Jeff Lillycrop, "Airborne lidar bathymetry: the SHOALS system," *Bulletin of the International Navigation Association* 103 (2000).

[5] For more information, see Irish, McClung, and Lillycrop, “Airborne lidar bathymetry: the SHOALS system.”

Naval demining operations may additionally benefit from LIDAR systems. Because of the imaging capability of LIDAR systems, such systems potentially allow improved discernment of mines from debris at long range. This can be achieved by systems on low-flying aircraft, UUVs, and/or surface ships.

State of Play

LIDAR systems are commercially available and are rapidly decreasing in cost. LIDAR modules intended for navigation tasks for drones and autonomous vehicles can be found for under $10,000, and typical “self-driving car” LIDAR modules are on the order of $50,000–$75,000. The cost of such systems will likely continue to decrease as the commercial applications of this technology expand.

Underwater LIDAR systems are far more niche but are emerging onto the commercial market for marine mapping, law enforcement, and recovery operations. Military versions of these systems may be in use, but little information is available on the extent of military marine LIDAR use. Improvements in laser diodes and detection mechanisms driven by the private sector likely will continue to lead to improvements in the range and scanning rate of these devices.

Structure-from-motion point cloud reconstruction (ViDAR) is a well-developed field, but because of constraints on computing power, this technology is highly limited. Although the sensing hardware exists in a mature form, the computation required to allow point-cloud generation in real time does not exist in a compact package. For example, reconstructing a 1x1m area surveyed with 30 images using VisualSFM (a free software package) takes 10-30min on a laptop.[6] As computing power continues to grow more efficient, this method will become increasingly viable as a means of mapping and navigation.

Space-based LIDAR systems are currently limited to fairly large satellites (hundreds of kilos) because of the laser and detector power requirements. However, as commercial lasers and detectors become ever more compact, smaller or even distributed LIDAR systems may become possible.[7]

Effects on Strategic Situational Awareness

LIDAR technologies can augment strategic situational awareness (SA) through improvements in mapping, detection, and navigation.

Mapping

Mapping systems offer improvements in *vantage*[8] and *range.* LIDAR systems offer the ability to map ground structures through cloud cover using aviation or space assets where optical sensors would fail. Further, LIDAR avoids many of the complexities of synthetic-aperture radar (SAR), though the data acquisition rate of currently declassified systems is much smaller than most SAR systems. In addition, LIDAR systems offer the ability to dynamically change their readout resolution. If an object of interest is acquired via a ground asset, a LIDAR

---

[6] Information from an example run that the author participated in at the Nahara Robotics Center in November 2018 to demonstrate the utility of SfM for mapping a mock up of the Fukushima pressure vessel pedestal in reactor #1.

[7] Xiaoli Sun, “Space-based lidar systems,” in Conference on Lasers and Electro-Optics 2012 Proceedings, (Optical Society of America, 2012), paper JWC.5, https://www.osapublishing.org/abstract.cfm?URI=CLEO_AT-2012-JW3C.5.

[8] To learn how this project defines the italicized terms, please visit the On the Radar website glossary, https://ontheradar.csis.org/glossary.

satellite can be directed to sample the area around the target at a high spatial frequency. In “search mode,” the LIDAR system would sample a much larger area at a lower spatial frequency.

Laser-based mapping systems also have the ability to improve *speed.* The ability of LIDAR/ViDAR systems to create 3D models of areas in real time offers rapid assessment of battle damage, improved route planning, and the ability to see changes in force posture in real time. Although the benefits of increased speed are more pronounced for tactical applications, this information is nonetheless important for understanding changes in force posture that may be indicative of overall strategy.

LIDAR mapping systems offer some improvements in *resiliency*. LIDAR systems can be designed to operate in bands where cloud interference is minimal. Likewise, these systems can be built to minimize smoke interference. As a result, it is much harder to interfere with LIDAR scans than it is to deploy anti-radar chaff or anti-optical observation smoke cover. These systems can also be deployed on small UAVs, meaning that even if space assets are compromised, 3D ground-mapping data can still be gathered. ViDAR mapping systems, because of their reliance on visual imagery, do not improve observation *resiliency*.

The *detectability* of most LIDAR mapping systems is somewhat high. Most LIDAR systems employ high-power IR emitters that are invisible to the eye (“eye-safe”) but detectable using simple equipment. Laser-detection equipment is even commercially available in the form of laser speed measurement detection equipment for automobiles. As a result, almost any adversary has a high likelihood of detecting LIDAR mapping in progress. This may compromise the location of the scanning platform and alert adversary forces to hide equipment.

The *precision* of LIDAR mapping data can be dynamically changed to meet the user’s desires. Higher spatial sampling frequency correlates to improved map accuracy, but at the cost of a lower data collection rate (measured in square kms/hr). As a result, the *precision* of these data can be much greater than most mapping assets, which are typically restricted to either precision or volume.

The p*ersistence* of LIDAR mapping systems is likely to be excellent when facing inclement weather or smoke, but poor in the face of active countermeasures. As shown by the proliferation of anti-LIDAR systems for commercial automobiles (to avoid speeding infractions), the technology needed to disrupt LIDAR is inexpensive and easy to build.

Detection

Detection applications of LIDAR include demining, IED detection, and chem/bio agent detection. These LIDAR implementations offer improvements in *vantage*, as detecting these threats traditionally requires close proximity. This *vantage* improvement offers enormously improved estimation of adversary strategy (ex: where are they mining first?) and escalation posture. Likewise, the improvements in detection lessen the time needed to detect changes in adversary behavior, which is best classified as an improvement to *speed*.

LIDAR based detection schemes offer improvements in *resiliency* because they are standoff technologies. Because these methods do not require physical access to the area under investigation, it is more difficult for adversary forces to prevent data being gathered on their activities.

These detection systems also present significant improvements in *precision* over existing detection methodologies, as they provide 3D models of the targets under investigation. In the context of naval demining operations, LIDAR provides improved discernment of mines from marine debris. In ASW applications, LIDAR offers a means of not only detecting, but identifying various submarines in shallow areas where sonic detection methods are limited. Though this capability improvement does not extend to deep-water SSBN hunting because of refraction and turbidity, the improvement in detection in coastal engagements may be significant.

Navigation

Navigation systems employing LIDAR provide massive improvements in *resiliency* and smaller improvements to *persistence* and *precision*. SLAM algorithm-based navigation does not rely on external signals (such as those from GPS) and therefore can operate even when jamming or anti-satellite warfare has rendered satellite navigation impossible. This provides a means of navigation that is robust even under extreme conditions such as a strategic nuclear exchange. In less extreme conditions, LIDAR navigation offers a means of checking external navigation signals for signs of tampering, which could help eliminate the GPS-spoofing attack channel (which is theorized to be how Iran captured a U.S. RQ-170).[9] In addition, LIDAR pose information can be used to back up accelerometer systems that may fail because of battle damage or malfunction.

Effects on Strategic Stability

In general, LIDAR systems are not intrusive, destructive, or clandestine. Depending on the nature of the information gathered, the data may offer information valuable for preemption or targeting. Though most LIDAR systems are highly *vulnerable* to intentional jamming, they offer a capability that is robust against most natural threats (cloud cover, smoke).

Mapping

Mapping LIDAR generally offers much more rapid assessment of terrain and structure. Therefore, it is a relatively low-risk technology for strategic situational awareness and stability. The improvement in information speed and quality associated with these devices is not likely to be destabilizing; although improvements in spatial information may be of great tactical importance, improved assessment of battle damage, materiel location, and terrain changes are not likely to affect the strategic balance. Likewise, peacetime uses of LIDAR mapping such as mass grave location, forestry monitoring, and aerosol characterization are not anticipated to be inflammatory.

In general, LIDAR systems are not intrusive, destructive or clandestine.

Detection

Like mapping systems, detection technologies based on LIDAR/ViDAR are minimally intrusive, non-destructive, and non-clandestine. They are highly vulnerable to jamming, but in uncontested environments offer significant improvements to detection capabilities.

Applications involving the geolocation of missile systems, determination of missile alert status, and verification of the use of chem/bio weapons all are improvements in situational awareness and are unlikely to have a large impact on stability. However, improvements to ASW capabilities have the potential to be destabilizing. Submarines currently stand as the most robust leg of the nuclear triad in U.S. and Russian forces. They are considered so robust that many have called for the elimination of the ICBM leg of the triad.[10] A reduction in submarine survivability would likely have significant effects on nuclear decisionmaking with respect to escalation and targeting. Although ASW LIDAR does not directly allow the detection of SSBNs when in deep water, the

---

[9] Adam Rawnsley, “Iran’s Alleged Drone Hack: Tough, But Possible,” *Wired*, December 16, 2011, https://www.wired.com/2011/12/iran-drone-hack-gps/.

[10] Scot J. Paltrow, "Special Report - Nuclear strategists call for bold move: Scrap ICBM arsenal," *Reuters*, November 22, 2017, https://www.reuters.com/article/us-usa-nuclear-icbm-specialreport/special-report-nuclear-strategists-call-for-bold-move-scrap-icbm-arsenal-idUSKBN1DM1D2.

improvement in detection in shallow water may restrict their movement in a crisis. Given sufficient development and deployment of this technology, states may come to believe that their second-strike capabilities have been degraded and therefore they must invest in larger arsenals. Furthermore, they may face “use it or lose it” pressure to launch nuclear assets early in a crisis.

Navigation

Navigation systems employing LIDAR/ViDAR gather minimal information about surroundings, and therefore are minimally intrusive and provocative. In some scenarios, robust navigation systems that require no external signals may in fact reduce escalatory behavior. By removing the dependence on satellites, these navigation systems disincentivize engaging in antisatellite warfare that targets dual-use navigation systems (which may convince an adversary a nuclear attack is underway). This technology may therefore contribute to situational awareness and stability by lowering incentives to attack certain satellite systems, all while improving the resiliency of a wide variety of platforms.

Conclusion

LIDAR and ViDAR technologies offer a means of rapid spatial data collection that can be used for a wide variety of detection, mapping, and navigation missions. The diverse commercial applications of LIDAR and ViDAR technologies make these devices inherently dual use between civilian and military applications. Because of sizable commercial investments in developing these technologies for autonomous navigation and UAVs, they are expected to rapidly improve in cost and data rate. Applications in mapping and navigation are unlikely to have a significant negative impact on strategic situational awareness and stability (and may in fact improve them). However, applications for littoral anti-submarine warfare could have a major impact on the survivability of the submarine leg of the nuclear triad. Though the market for underwater LIDAR systems is small, advances in this field have the potential to have destabilizing consequences. As a result, advancements in underwater and air-to-water LIDAR systems should be monitored closely.